A CORPORATE STRUCTURE FOR COMBINING POWER FROM 3^N OSCILLATORS

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Summary

The output power from three Gunn oscillators was combined with a short-slot coupler with power combining efficiency of about 100 percent at 9.7 GHz. Using the 3-oscillator structure as the building-block, we constructed (3^2=)9-oscillator corporate structure and (2×4+1=)9-oscillator tandem structure to demonstrate power combining efficiency of 92 and 95 percent, respectively, at 9.6 GHz.

Introduction

Various techniques for combining power from microwave solid-state sources have been described by many authors over the years[1-9]. Some of the techniques, most notably, the single-cavity-multiple-device techniques of Kurokawa-Magalhaes and Harp-Stover, have gained practical importance to fulfill a class of communication and radar transmitter requirements during the last several years. Nevertheless, interest persists in searching for new high-efficiency power combining techniques that would offer possibilities of achieving higher power at higher frequencies. This paper describes a new method of combining power from multiple oscillators using short-slot couplers[10] in conjunction with high-level injection locking. It is intended that the present method is compatible with the single-cavity-multiple-device techniques to multiply the total number of devices combined.

Principles

Three identical oscillators and a matched load are connected to a four-port hybrid coupler to form a 3-oscillator structure as shown in Fig.1(a), where the coupler symbol represents the short-slot coupler shown in Fig.1(b). Let the oscillator 1 generate power, P_1, at a frequency, f_1. P_1 is equally divided and injected into the oscillators 2 and 3, resulting in a frequency-locked oscillation when tuned properly. The output power from the oscillators 2 and 3 under a high level injection signal varies as their free-running oscillation frequencies, f_2 and f_3, respectively, deviate from f_1[11]. According to our experiments, the output power from the oscillators 2 and 3 takes the maximum values of about $P_2+P_1/2$ and $P_3+P_1/2$ at frequencies near the lower ends of their locking ranges, where P_2 and P_3 are the output power from the respective oscillators under free-running conditions. Since the injection signals of equal magnitude into the identical oscillators 2 and 3 have a 90-degree phase difference, the power wave associated with $P_2+P_1/2$ at the port 2 leads that associated with $P_3+P_1/2$ at the port 3 by 90 degrees. Consequently, the power is summed at the port 4 to deliver the combined power, $P_c=P_1+P_2+P_3$, to the load and cancelled at the port 1 to inject no power into the oscillator 1. It is worth mentioning that the high-level injection from the locking oscillator 1 into the locked oscillators 2 and 3 with no reverse injection improves the stability of the circuit operation over that of the conventional 2-oscillator combining circuit.

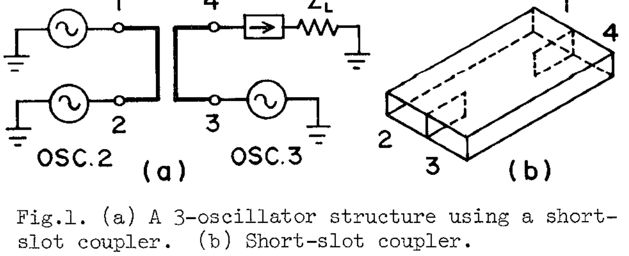

Fig.1. (a) A 3-oscillator structure using a short-slot coupler. (b) Short-slot coupler.

The above principles can be extended to a larger number of oscillators. If we replace all the oscillators with three of the 3-oscillator structures, we obtain a 9-oscillator corporate structure shown in Fig.2. In principle, it is possible to form a corporate structure in which 3^N oscillators are combined with $(3^N-1)/2$ couplers in this way. Another possibility is to replace the oscillator 1 alone with the 3-oscillator structure. In this way, it is possible to form a tandem structure in which 2N+1 oscillators are combined with N couplers. A 2×4+1=9-oscillator tandem structure is shown in Fig.3.

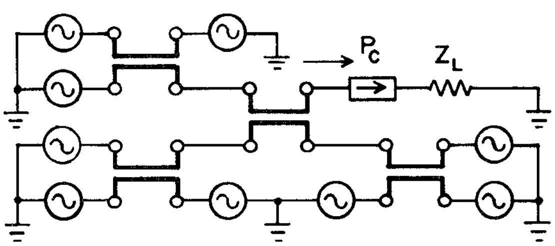

Fig.2. A 9-oscillator corporate structure.

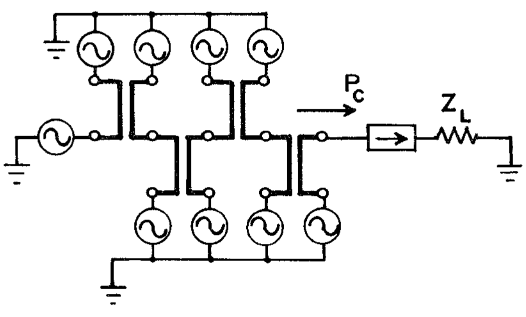

Fig.3. A 9-oscillator tandem structure.

Experiments

Experimental power-combining structures were built using a standard rectangular waveguide (22.9 mm × 10.2 mm) and X-band Gunn diodes (NEC GD511AA, 10-20 mW).

Fig.4 illustrates the construction of an experimental 3-oscillator structure, where the Gunn oscillators are of the post-mount type having a dielectric rod for tuning. The coupling slot is 35-mm long. The oscillator section and the coupling section are joined by the flanges to allow direct access to the individual oscillators. The 3-oscillator structure can be adjusted for the maximum output power at a prescribed frequency, f_c, by the following steps: (1) Operate the oscillator 1 alone and tune f_1 to a frequency slightly above f_c. (2) Operate all the oscillators and adjust the tuning rods of the oscillators 2 and 3 for maximum power at f_c. The adjustment requires iteration. (3) Tune the oscillator 1. If the combined output power becomes maximum at f_c, terminate the adjustment. (4) If not, tune the oscillator 1 to bring the combined oscillation frequency closer to f_c and repeat the above steps (1)-(3).

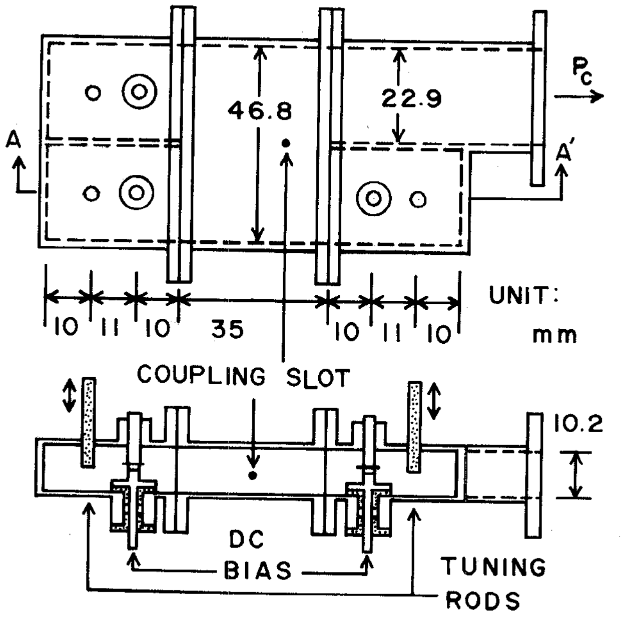

Fig.4. Construction of an experimental 3-oscillator structure using post-mount Gunn oscillators and a short-slot coupler.

Typical results of such circuit adjustment in which f_c was set at 9733 MHz are summarized in Table 1, where P_c is the combined power given in mW. The output power and oscillation frequencies of the individual oscillators, measured directly after dismantling the optimized circuit by the flanges, are given in the P_1,P_2,P_3,Δf_1,Δf_2 and Δf_3 columns, where $\Delta f = f_i - f_c$ (i=1,2,3). The power combining efficiency, η, defined by

$$\eta = \frac{P_c}{P_1 + P_2 + P_3} \times 100 \quad (\%)$$

is also given. In all the cases, the power combining efficiency of about 100 percent was obtained.

Table 1.
Results of power combining experiment at f_c=9733 MHz using the structure of Fig.4.

	Free Running						Combined	
	Freq.Deviation: (MHz)			Power (mW)			Power (mW)	Eff. (%)
No.	Δf_1	Δf_2	Δf_3	P_1	P_2	P_3	P_c	η
1	+11	-19	-13	21.0	28.0	25.5	73.0	98
2	+10	-22	-16	19.0	18.0	19.0	58.0	103
3	+11	-23	-18	22.5	22.5	17.5	63.0	101
4	+14	-24	-16	21.0	28.0	23.5	72.0	99
5	+ 9	-18	-16	24.7	23.3	23.1	72.0	101

Experimental 9-oscillator corporate and 9-oscillator tandem structures we have built are illustrated in Figs.5 and 6, where the oscillator construction is identical to that shown in Fig.4. The capacitive screws to provide the correct 90-degree phase shift were found necessary for the couplers in the multistage tandem structure.

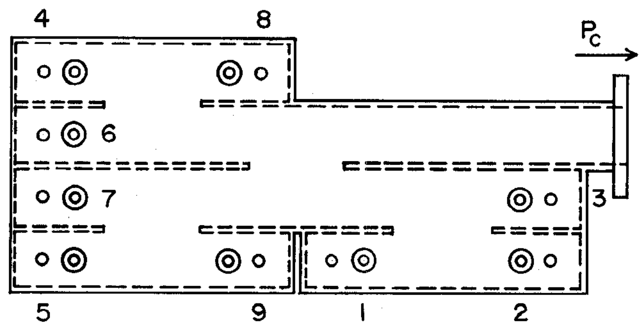

Fig.5. An experimental 9-oscillator corporate structure.

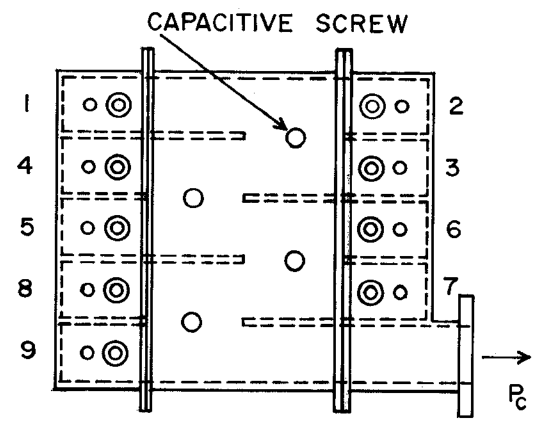

Fig.6. An experimental 9-oscillator tandem structure.

The circuit adjustment can be made by tuning the oscillators in turn suggested by the numbers assigned to them. The adjustment requires iteration. Results of power combining experiments are presented in Fig.7, where the combined power, P_c, given in mW is plotted along the ordinate and the sum of output power from the individual oscillators along the abscissa. In Fig.7, the crosses represent the results from the corporate structure and the open circle from the tandem structure. Both structures can combine the output power from 3,5,7 and 9 oscillators. This is demonstrated using the corporate structure. The numbers in the figure indicate the oscillators in operation.

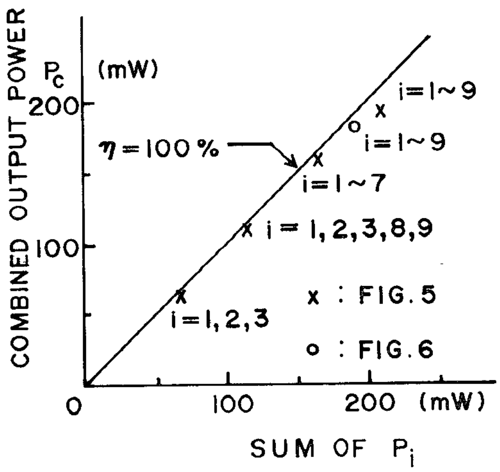

Fig.7. Results of power combining experiments using the 9-oscillator corporate and tandem structures shown in Figs.5 and 6. The numbers in the figure indicate the oscillators in operation.

Power combining efficiency of 92.4 percent at f_c=9610 MHz and 95.3 percent at f_c=9620 MHz was obtained with 9-oscillator corporate and 9-oscillator tandem structures, respectively.

The power combining efficiency of the combining networks (assuming 100-percent efficiency for the power combining through injection locking) is estimated for the 3^N-corporate and 2N+1-tandem structures assuming a loss of -0.1 dB per pass, and the results are represented by the solid curves in Fig.8, where the number of oscillators combined is plotted along the abscissa. The broken curves are the plots for the 2^N-corporate structure, the chain combining structures using directional couplers and circulators,

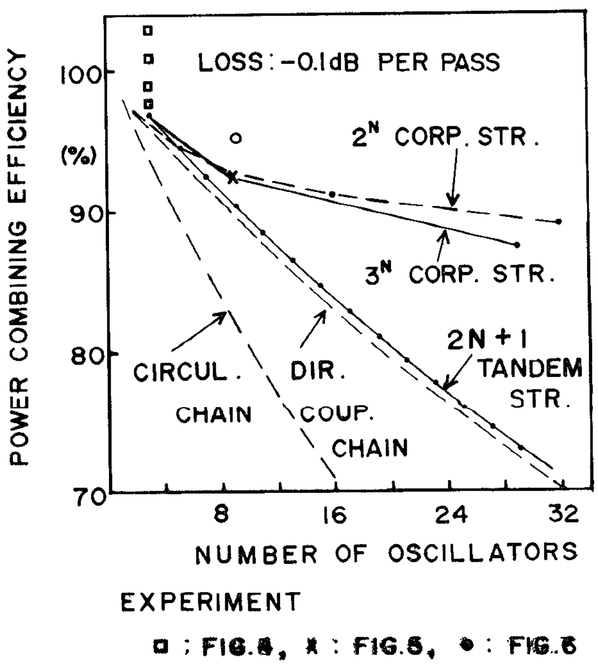

Fig.8. The power combining efficiency versus the number of oscillators combined for various combining networks.

all assuming -0.1 dB per pass, for comparison. The experimental results obtained with the 3-oscillator, 9-oscillator corporate and 9-oscillator tandem structures are represented by the boxes, crosses and open circle, respectively.

All these circuits readily generate the combined power upon application of dc bias with no need for readjustment once they are adjusted.

The injection signal levels are high in the 3-oscillator and 9-oscillator tandem structures, and the stability of operation of these circuits may be stated as good or fair. But, the stability of the 9-oscillator corporate structure may become marginal when the injection signals into the oscillators 8 and 9, referring to Fig.5, are made too weak.

Conclusions

A method of combining power from 3, 3^N and 2N+1 oscillators has been developed using short-slot couplers in conjunction with high-level injection locking. The principles of the method were supported by the experiments using X-band Gunn diodes. Experiments are planned and in part under way currently on applications of the method to IMPATT, single-cavity-multiple-device and millimeter-wave oscillators.

Acknowledgment

The authors would like to thank K.Sekido and S.Agu of Nippon Electric Co. for supplying the diodes used in the experiments.

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